NAG 5-10773: Summary of Research

CIZA: The First Systematic X-Ray search for Clusters of Galaxies Behind the Milky Way

1 Research goals

The aim of the CIZA project (Clusters In the Zone of Avoidance) was to take the first step toward a complete X-ray census of clusters of galaxies behind the plane of the Galaxy ($|b| \leq 20°$), the historical "Zone of Avoidance" of optical extragalactic surveys. Finding these heavily obscured clusters in ROSAT All-Sky Survey data would allow us to

1. construct the first truly all-sky, statistically complete, X-ray flux limited sample of galaxy clusters
2. use this sample to obtain an improved measurement of the cluster dipole (both amplitude and direction)
3. chart large-scale structure across the plane of the Milky Way as traced by galaxy clusters
4. identify potentiall massive galaxy clusters contributing to the observed large-scale flow pattern in the local universe, specifically in the region around the Great Attractor
5. use least-action modelling to deduce the gravitational fields created by galaxy clusters and compare this reconstruction with the one obtained from local galaxy surveys.

As summarized in the following, our project was hugely successful in demonstrating the feasibility of this undertaking and allowed substantial progress toward achieving the stated science goals.

2 Project results

In this pilot study we focused on the subsample of the X-ray brightest systems with $f_{\rm X,BSC} > 5\times10^{-12}$ erg cm^{-2} s^{-1}. Sources above this flux threshold were targeted at high priority in our follow-up efforts, to the effect that the identification of these brightest X-ray sources is now essentially complete. Our findings are discussed in detail by Ebeling, Mullis & Tully (2002).

2.0.1 Statistical properties of the CIZA bright cluster sample

Of the 481 BSC sources in the X-ray bright list, 73 have been identified as clusters of galaxies; 71 of these now have spectroscopic redshifts. Among them are all previously known X-ray bright clusters in this area, such as the Ophiuchus, Triangulum Australis, 3C129.1, Cygnus-A, and PKS0745−191 clusters, as well as AWM 7, but also the Abell clusters A426 (Perseus), A539, A644, A2319, A3392, A3411, A3627, and A3628. The majority of all *CIZA* clusters are, however, new discoveries: 73% of the clusters in the X-ray bright sample were previously unknown. The spatial distribution of these

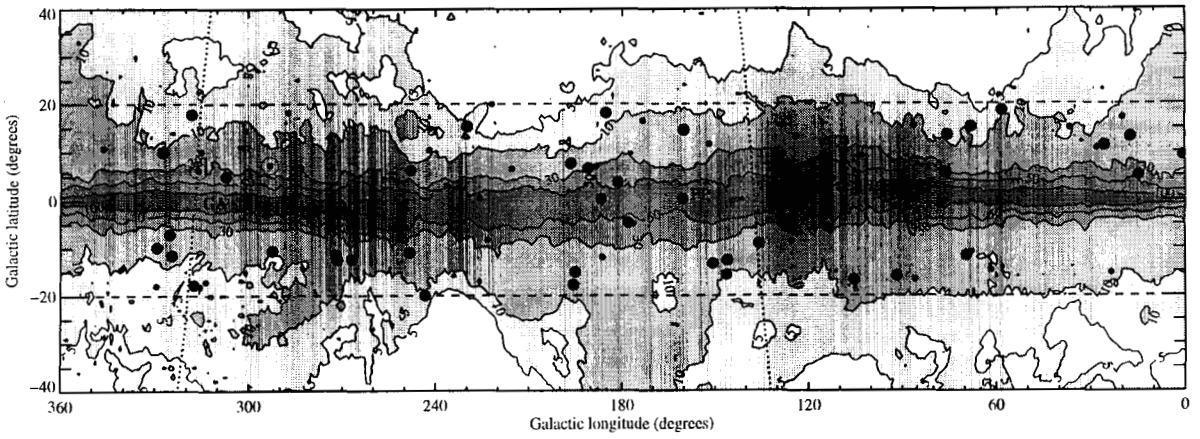

Figure 1: The locations of the 73 *CIZA* clusters with BSC detect fluxes greater than 5×10^{-12} erg cm^{-2} s^{-1} (0.1–2.4 keV) found in our pilot study. Systems relevant for LSS studies of the local universe ($z < 0.075$) are shown as filled circles; more distant clusters are shown as open circles. Two clusters without spectroscopic redshifts are circled. The underlying grey-scale map shows the distribution of Galactic $n_{\rm H}$.

systems is shown in Fig. 1, overlaid on a map of the equivalent column density of neutral Hydrogen. Note how CIZA succeeds in detecting clusters in all but the most extinguished regions of our study area.

The limited depth of the ROSAT All-Sky Survey data does not always allow us to unambiguously confirm that the X-ray emission is indeed extended and diffuse; however, a thorough visual inspection of the RASS data for all 73 systems suggests that no more than five are significantly contaminated by point source emission.

The redshift distribution of the 71 *CIZA* clusters with BSC fluxes $f_{\rm X,BSC} > 5 \times 10^{-12}$ erg cm^{-2} s^{-1} and measured redshifts is shown in Fig. 2. Comparing the observed with the expected redshift distribution (based on the abundance of clusters in the extragalactic sky as measured by the BCS project) we find that our identification procedure has obviously missed clusters in the zone of avoidance: 71 (73 if the remaining two candidates can be spectroscopically confirmed) were found where 101.1 are expected. This level of incompleteness is not entirely unsuspected though. Although we have demonstrated that we are able to detect clusters at much higher efficiency in the X-ray waveband, we still require imaging confirmation at optical and/or NIR wavelengths and, finally, spectroscopic redshifts. For nearby clusters these follow-up observations are feasible even at very low Galactic latitude, but more distant systems or X-ray selected cluster candidates behind the very plane of the Milky Way may be impossible to confirm in the optical. The resulting redshift dependence of the survey's completeness is apparent in Fig. 2: although we appear to be missing one in four clusters overall, *CIZA* is doing very well at low redshift. At $z < 0.075$ (a limit beyond which the distribution of clusters has negligible effect on the local gravitational field and the resulting large-scale flows), the X-ray bright *CIZA* subsample compiled in our pilot study is complete compared to the model predictions (41 observed, 38.6 predicted).

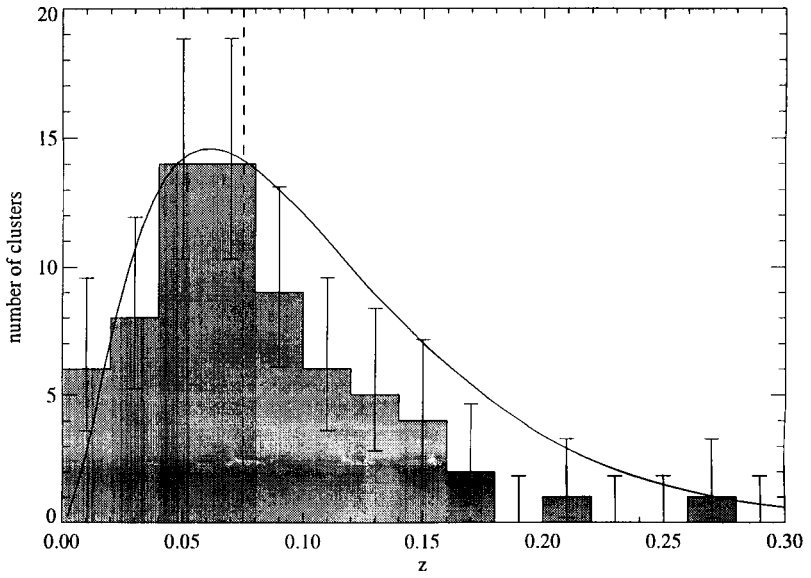

Figure 2: Distribution in redshift space of the 71 *CIZA* clusters with BSC fluxes $f_{\rm X,BSC} > 5 \times 10^{-12}$ erg cm^{-2} s^{-1} and measured redshifts. The solid line shows the expected distribution for a 100% complete sample predicted from the BCS cluster X-ray luminosity function (Ebeling et al. 1997). The dashed line at $z = 0.075$ ($cz = 22,500$ km s^{-1}) marks the redshift beyond which the spatial distribution of galaxy clusters is likely to have negligible effect on local large-scale flows. Error bars show the 1σ Poisson uncertainties.

2.0.2 The GA region

The region around A3627, the cluster often referred to as being at the heart of the Great Attractor, is of special interest for LSS studies in the local universe (see also Introduction). Although the galaxy distribution around A3627 has recently been charted in great detail (Woudt et al. 1999, and references therein) the full extent of the GA is still unknown.

The discovery of CIZA J1324.6–5736, another massive cluster of galaxies in the GA region indicates that the mass concentration is yet greater and more extended than was previously thought. At $l = 307.4$ deg, $b = 5.0$ deg, and $cz = 5700$ km s^{-1}, this newly discovered cluster CIZA J1324.6–5736 is similarly X-ray luminous ($\approx$ massive) and at the same distance as A3627, but situated on the other side of the Galactic equator, 21.6 deg (19.7 h^{-1} Mpc) away in the plane of the sky. Despite recent galaxy redshift surveys in this area (Kraan-Korteweg & Juraszek 2000) showing a pronounced galaxy overdensity roughly at the position of CIZA J1324.6–5736, the system was not previously recognized as a massive cluster.

Fig. 3 shows an overlay of the X-ray contours (from a serendipitous deep ROSAT HRI pointed observation) and an R band image of the cluster core. The pronounced peak of the X-ray emission at the position of the brightest cluster galaxy suggests the presence of a cooling flow, a phenomenon typical of centrally concentrated, dynamically relaxed galaxy clusters.

The location of CIZA J1324.6–5736 in the GA region points to an intriguing connection to both A 3627 and the Centaurus cluster, A 3526. In projection, CIZA 1324.6–5736 lies about half way

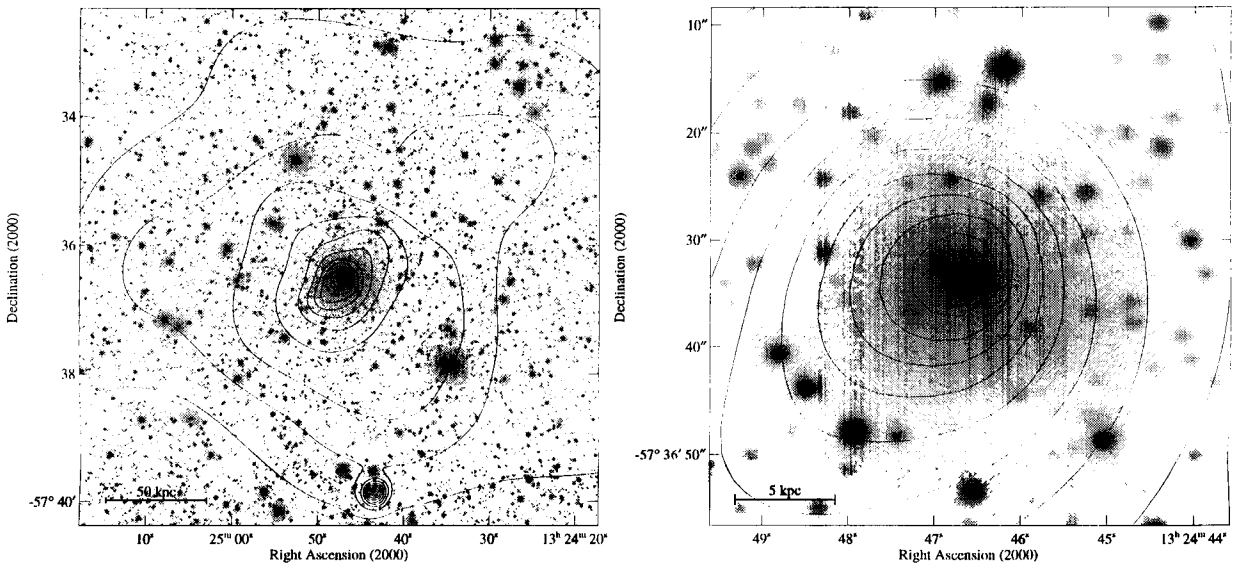

Figure 3: Optical (R band) image of the newly discovered cluster CIZA J1324.6–5736 as obtained with the CTIO 1.5m telescope in a 12 minute exposure. We show the full optical image (left) as well as a zoomed-in view of the very cluster core (right). Overlaid are adaptively smoothed and logarithmically spaced contours of the cluster's X-ray emission as detected with the *ROSAT* HRI in a 34.5 ks pointed observation. Two concordant redshifts of $z \sim 0.019$ were measured for this system in April 2000. We have adjusted the astrometry of the X-ray image by 3.5" (well within the typical astrometrical error of HRI observations) to align the bright point source south of the cluster with its obvious optical counterpart. Note the pronounced X-ray peak and its perfect alignment with the cluster cD, suggestive of an emerging cooling flow. (Ebeling et al. 2002)

between A 3627 and the Centaurus cluster which is situated at (l, b, v) =(302.4, 21.6, 3300 km s^{-1}). If we interpret the differences in the observed radial velocities of these systems as being caused entirely by the Hubble flow, the three clusters form an almost perfect equilateral triangle with sides spanning about 26 h^{-1} Mpc, viewed nearly edge on.

A second important discovery of the *CIZA* survey in the GA region may hold the key to an improved understanding of the observed large-scale flows toward a vertex at $z \sim 0.05$, i.e., *behind* the GA. We discovered a previously unknown cluster, CIZA J1652.9–5943 (see Fig. 4), at the same redshift ($z \sim 0.05$) as, but 5 deg (11.9 h^{-1} Mpc) away from the Triangulum Australis cluster, which, as mentioned before, is one of the most X-ray luminous clusters in the local universe. As in the case of CIZA J1324.6–5736 and A 3627 (see above), the newly found cluster is comparable in luminosity to its famous neighbor Triangulum Australis and thus likely similarly massive. In projection on the sky, Triangulum Australis is only 4.4 deg away from A3627, i.e., very close to the apparent vertex of the observed bulk motion that may continue *beyond* $cz \sim 6000$ km s^{-1}, the approximate distance of the GA.

We discovered two more clusters at very similar redshift ($z \sim 0.05$) on the opposite side of the Galactic plane. Again, there is thus intriguing evidence for a massive structure crossing the plane at about $l = 330$ deg. Future follow-up observations of these systems will be required to test whether

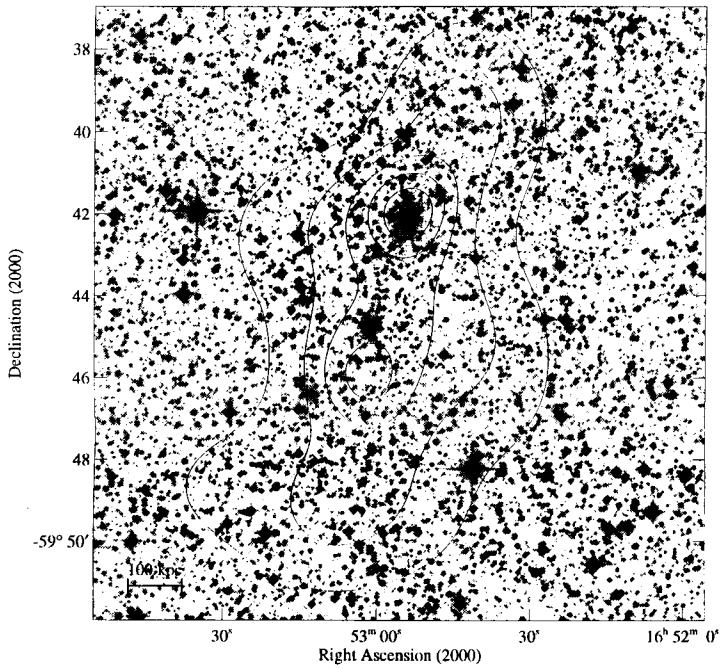

Figure 4: Optical (DSS) image of the newly discovered cluster CIZA J1652.9–5943. Overlaid are adaptively smoothed and logarithmically spaced contours of the cluster's X-ray emission as detected with the ROSAT HRI in a 7.5ks pointed observation. We measured concordant redshifts of $z \sim 0.048$ for this system as part of this study.

they are indeed part of a single structure that might contribute to the reported bulk motion of Abell clusters in this direction.

3 Outlook

Despite the enormous success of this one-year pilot project CIZA was not selected for continued funding from the ROSS-2002 Astrophysics Data Program. We shall try again to secure funding to continue and complete this research in 2003 (ROSS-ADP 2003).

4 References

Ebeling H. et al. 1997, ApJ, 479, L101
Ebeling H., Mullis C.R., Tully R.B. 2002, ApJ, 580, 774
Kraan-Korteweg R.C. & Juraszek S. 2000, PASA, 17, 6
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5 Publications

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Kocevski D., Mullis C.R., Ebeling H. 2003, ApJ, submitted